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Conclusions on the filtering action of forests from ecosystem analysis (*)

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RÉSUMÉ

A partir des flux d'éléments minéraux dans l'écosystème hêtraie du district de Solling (Europe centrale) l'action de filtrage vis-à-vis de la pollution de l'air (SO_2 et aérosols) a été calculée. Les flux suivants ont été utilisés : apports par les précipitations à découvert et sous couvert, chutes de litières, fixation dans la biomasse, perte par drainage. Les valeurs utilisées sont des valeurs moyennes d'une période de mesure de trois ans. Une remarquable action de filtrage a été calculée pour Na (3,4), K (4,8), Ca (6,4), Mg (0,6), Mn (0,8), Al (0,1), Cl (13,2), S (14,2), P (0,2), N (3,6) (chiffres en kg par ha par an).

SUMMARY

From the fluxes of chemical elements in the ecosystem the filter action of a beech forest in the Solling district (Central Europe) for air pollutions (SO_2 gas and aerosols) was derived by calculations. The following fluxes have been used : input by precipitation, precipitation within stand, litterfall, increment in stand, percolation output. The values used are mean values of a three years measuring period. A remarkable filter action has been calculated for (values in kg element per ha and year) Na (3.4), K (4.8), Ca (6.4), Mg (0.6), Mn (0.8), Al (0.1), Cl (13.2), S (14.2), P (0.2), N (3.6).

ZUSAMMENFASSUNG

Aus den Flüssen der chemischen Elemente im Ökosystem wird die Filterwirkung eines Buchenbestandes im Solling auf Luftverunreinigungen (SO_2 und Aerosole) durch Berechnungen abgeleitet. Dabei finden die folgenden Flüsse Verwendung : Input durch Niederschlag, Transport mit Bestandesniederschlag und Streufall, Transport in den Zuwachs, Output durch Tiefensickerung. Die verwendeten Daten sind Mittelwerte über eine Meßperiode von 3 Jahren. Es ergibt sich eine beachtliche Filterwirkung für (Werte in kg Element pro ha und Jahr) Na (3,4), K (4,8), Ca (6,4), Mg (0,6), Mn (0,8), Al (0,1), Cl (13,2), S (14,2), P (0,2), N (3,6). Aus der Input-Output-Analyse werden weitere Schlußfolgerungen über Vorratsveränderungen im Boden (Abnahme oder Vermehrung) gezogen.

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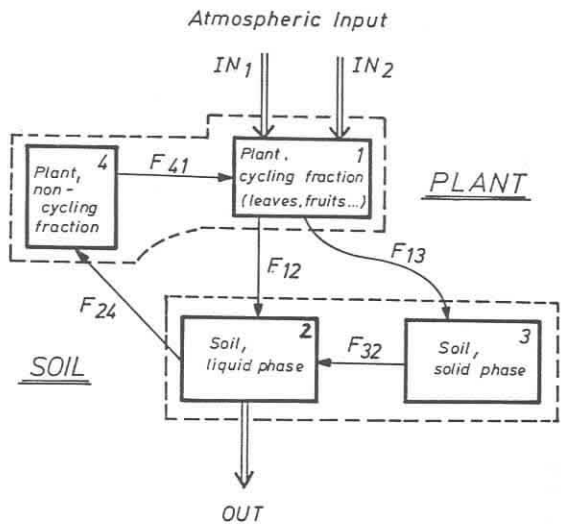
INTRODUCTION

The filter effect of a forest ecosystem with regard to substances carried within the atmosphere results from physical and chemical interaction between the ecosystem and its environment. It is of importance with regard to atmospheric pollution, which is reduced by this filter effect, as well as to the chemical status of the plant material and of the soil and to the quality of the percolation water leaving the ecosystem to become, subsequently, part of the groundwater pool.

Figure 1 shows a compartment model of a forest ecosystem, subdivided into two submodels — plant and soil —, both of which are again subdivided into different compartments. The boxes (compartments) are connected by arrows,



Atmospheric input

IN_1 - with precipitation
IN_2 - with aerosols and gases

Output

OUT - with percolation

Internal fluxes

F_{12} - with precipitation inside the stand
F_{13} - with litterfall
F_{32} - mineralization desorption, weathering dissolution
F_{24} - root uptake
F_{41} - turnover

FIG. 1. — Compartment model for mineral cycling in a forest ecosystem.

representing flows of chemical elements (Na, K, Ca, Mg, Fe, Mn, S, Cl, P). Exchange of elements of the ecosystem with its environment (input and output) is represented by double line arrows. Each compartment contains, at a given time, a distinct amount of each element (store).

The atmospheric input of elements has to be separated, for methodical reasons, into two fractions :

1) input by precipitation of any kind (rain, snow, dust etc.) = input by open field precipitation

2) input with gases and aerosols that are adsorbed, intercepted or filtered out within the ecosystem.

In the present case, the only output for the element under consideration is with the percolation water.

Each surface area, forested or unforested, receives an atmospheric input of elements from air-borne substances carried across that area and precipitating on it. The forest ecosystem would act as a filter whenever its atmospheric input per unit area is greater than on nonforested area in the same environment.

SITE DESCRIPTION

The research site — a 125 years old beech forest (*Fagus silvatica*) is located in the Solling mountains at 500 meters above sea level. Annual rainfall is about 1100 mm, average temperature is 6,5 °C. The soil is a two-layered acid Braunerde developed in a periglacial loess loam (0-60 cm) over solifluction masses consisting mainly of weathered Buntsandstein (60-140 cm) over Buntsandstein (triassic sandstone). For a more detailed site description see ELLENBERG (1971) and BENECKE and MAYER (1971).

METHODS

Input, output and fluxes of elements within the ecosystem, as given in figure 1, were measured in the following ways (cf. MAYER, 1971) :

IN_1 : The atmospheric input with open field precipitation is measured by collecting precipitation in rain gauges on a clearcut area close to the research

stands. Samples are taken after each precipitation, lumped together for monthly samples and analysed. Annual values in kg/ha, year are given in table 1 (1).

TABLE 1

Annual fluxes and increments in the Solling beech site
(Age of stand: 125 years. Average values June 1969 - May 1972)

	Na	K	Ca	Mg	Fe	Mn	Al	Cl	S	P	N
					kg/ha, year						
(1) Open field input IN_1	6.6	3.7	12.6	2.6	0.9	0.2	2.8	15.1	22.2	0.5	21.8
(2) Precipitation F_{12} in the beech stand	12.2	22.4	26.3	3.9	1.3	3.1	3.3	32.5	46.1	0.5	22.1
(3) Litterfall F_{13}	0.7	16.0	16.2	1.5	1.8	5.1	0.5	0.8	3.2	4.0	49.4
(4) Percolation OUT output	7.4	1.4	10.2	2.4	0.1	3.7	8.0	29.3	17.7	0.04	4.1
(5) Wood increment C4	0.1	6.6	7.7	1.7	0.4	3.4	0.1	0.1	0.5	2.1	13.1
(6) $F_{12} - IN_1$	5.6	18.7	13.7	1.4	0.4	2.9	0.5	17.4	23.9	0.	0.3
(7) Filter action IN_2	3.4	4.8	6.4	0.6	0.6	0.8	0.1	13.2	14.2	0.2	3.6
(8) Non-litter-turnover $F_{12} - IN_1 - IN_2$	2.2	13.9	7.3	0.8	–	2.1	0.4	4.2	9.7	–	–

F_{12} : The flux of elements coupled with precipitation within the stand at the forest floor, consisting of stemflow, canopy drip and throughfalling precipitation, is collected by stemflow collectors and rain gauges distributed in the stands. Level of collection was ca. 30 cm above soil surface. Annual values in kg/ha, year are given in table 1 (2).

F_{13} : Litterfall, collected by litter traps and analysed monthly or in shorter periods (HELLER, 1971) Annual values are given in table 1 (3).

OUT : Output with percolation water below the rooting zone (90 cm depth) was collected by tension lysimers with pressure control following the suction of the soil water measured by tensiometers. The lysimeters were installed in a way that the soil and roots above the lysimeters were not disturbed. Annual values are given in table 1 (4).

There is no simple way to measure directly the fluxes F_{32} (mineralization, desorption etc.), F_{24} (uptake by plant roots), F_{41} (translocation within the plant) and IN_2 (filtering of gases and aerosols). But there are indirect ways to come,

at least, to reasonable estimates of these fluxes. This paper deals with the evaluation of F_{41} and IN_2, for the magnitude of IN_2 is a measure for the filter action of a forest.

SEPARATING INPUT FROM TURNOVER

Our understanding of the cycling in a forest ecosystem, as expressed by the compartment model in fig. 1, is such that the atmospheric input (IN_1 and IN_2) is intercepted by the surfaces of the trees, thus becoming part of compartment 1 (cycling fraction). The interception may occur by dissolution (of gases in surface water films), adsorption (of aerosols on plant surfaces) and assimilation (of gases in cells). We may, for the beginning, assume that assimilation as well as absorption of dissolved or adsorbed substances by the leaves and translocation to the non-cyling fraction plays only a negligible role.

Furtheron we have evidence, that at a given time of the year — say july 1 — the store of compartment 1 does not change over the years (steady state). Then the sum of the fluxes going into compartment 1 is equal to the sum of the outgoing fluxes

$$IN_1 + IN_2 + F_{41} = F_{12} + F_{13} \tag{1}$$

$$\text{Rearranging (1) to } IN_2 + F_{41} = F_{12} + F_{13} - IN_1 \tag{2}$$

we see that assesment of the filter effect of the forest ecosystem means separating turnover, F_{41}, from input with gases and aerosols, IN_2. For elements forming soluble salts it seems justified to eliminate the litterfall F_{13} from (2) since litter is certainly part of the biomass turnover and not directly dependent from the input. If we call the non-litter part of the turnover

$$U = F_{41} - F_{13}$$

we can write instead of (2)

$$IN_2 + U = F_{12} - IN_1 \tag{3}$$

The difference on the R.H.S. of (3) is calculated in table 1 (6). It is, relatively to the input IN_1, very considerable for all elements with the exception of phosphorus and nitrogen. So at least for these two elements it can be said, that the input with aerosols must be close to zero, and the turnover is restricted mainly to production of litter (cf. ULRICH, 1966).

For the remaining elements we can assume that outside the vegetation period the role of turnover for the bioelement amounts in canopy drip will be negligible. This assumption seems to be quite safe since for the beech stand the transpiration stream (transport medium for elements leached from crown) as well as the crown surface available for leaching is very small during winter months compared to the vegetation period. The latter is not true for the stemflow fraction of the flux F_{12}. In addition to this, the transfer of elements into the stemflow by decay and desorption of organic matter may play an important role also in winter. From this we may follow that for the winter months the relationship

$$IN_2 \cong F_{12}^* - IN_1 \qquad (4)$$

where $F_{12}^* = F_{12}$ — (elements in stemflow), is a good assumption.

No similar relationship can be deduced for the summer months. The interception may be determined mainly by area and physical condition of crown surface and the number and size of particles (aeorosols, gas molecules). It is likely that in a clean air region like the Solling district the meteorological conditions regulating number and size of the aerosols as well as the physical condition of the crown surface is of much greater importance for the interception of elements than the area of the crown surface. If this is true, the interception during summer should in the same way be related to IN_1 as during winter, that is IN_2/IN_1 should remain constant during the year. The wash-out of the atmosphere is considered here to be of comparable nature to the filtering of the air by the crown surface, both processes being influenced by the same meteorological parameters (cf. WOLAUER et *al.*, 1972).

To separate IN_2 (input with aerosols) from U (non-litter part of the turnover), the following evaluations have been made using monthly values for the inputs and fluxes :

Seperately for the winter months (November - April) and for the summer months (May - October) the ratio of the flux F_{12} (precipitation in the stand) and the Input IN_1 (open field precipitation), F_{12}/IN_1, was calculated (table 2). For the same time periods the difference ($F_{12} - IN_1$), the equivalent fractions of the cations, and the concentrations in the flux F_{12} and the input have been calculated (table 3, fig. 2, table 4, resp.).

TABLE 2

Ratio F_{12}/IN_1 (mean values, June 1969 - May 1972)

	Na	K	Ca	Mg	Fe	Mn	Al	Cl	S	P	N
Winter (Nov. – Apr.)	1.9	3.3	1.7	1.4	1.9	7.7	1.2	2.2	2.2	1.4	1.3
Summer (May – Oct.)	1.9	8.6	2.5	1.6	1.2	24	1.2	2.1	2.0	0.6	0.8

TABLE 3 (a)

Difference ($F_{12} - IN_1$) (mean values, June 1969 - May 1972)

SK	Na	K	Ca	Mg	Fe	Mn	Al	Cl	S	P	N
					kg/ha, year						
Winter (Nov. – Apr.)	3.6	3.9	5.1	0.57	0.34	0.46	0.17	11.1	11.7	0.07	2.6
Summer (May – Oct.)	2.0	14.9	8.6	0.71	0.10	2.4	0.30	6.4	12.2	-.15	-2.3

TABLE 3 (b)

Difference ($F^*_{12} - IN_1$) *and Ratio* $R = IN_{2(w)}/IN_{1(w)}$

	Na	K	Ca	Mg	Fe	Mn	Al	Cl	S	P	N
					kg/ha, year						
Winter (Nov. – Apr.)	2.2	2.2	3.5	0.3	0.25	0.3	0.05	8.2	6.7	0.06	1.6
Summer (May – Oct.)	1.2	2.6	2.9	0.3	0,35	0,5	0.05	5.0	7.5	0.13	2.0
$R = IN_{2(w)}/IN_{1(w)}$	0.5	1.3	0.5	0.23	0.66	4.3	0.03	0.9	0.64	0.38	0.16

TABLE 4

Mean concentrations (Average values June 1969 - May 1972)

Season		Na	K	Ca	Mg	Fe	Mn	Al	Cl	S	P	N
						µg/ml						
IN_1	Winter (Nov. – Apr.)	0.90	0.36	1.45	0.28	0.08	0.014	0.34	1.98	2.22	0.03	2.06
	Summer (May – Oct.)	0.43	0.36	1.60	0.23	0.92	0.02	0.22	1.05	2.15	0.06	2.22
F_{12}	Winter (Nov. – Apr.)	1.92	1.35	2.87	0.46	0.17	0.13	0.43	4.92	5.36	0.06	2.97
	Summer (May – Oct.)	1.02	4.00	3.40	0.46	0.14	0.60	0.36	2.87	5.65	0.05	2.32

RESULTS

According to the difference and similarities of their seasonal dynamics the elements may be arranged in the following groups :

— N and P.

As already mentioned above, the flux F_{12} of these elements differs only little from the input IN_1. During the summer months F_{12} is even smaller compared to IN_1. The average annual concentration of N and P in the precipitation within

the beech stand (flux F_{12}) increases to the same degree compared to the open field precipitation concentration (IN_1) as the amount of water decreases by evaporation (interception of the beech canopy).

— Na, Mg, Fe, Al, Cl and S.

For these elements F_{12} is much greater than IN_1 : the flux F_{12} is 1.2 times (Al) to 2.2 times (Cl) as big as the input IN_1. Comparison between winter and summer shows, that this effect is more or less the same during the year. Only Fe shows a considerably higher increase within the flux F_{12} during the winter months.

— K, Ca and Mn.

For these elements, too, the flux F_{12} is much greater than the input IN_1 (up to 18 times in the case of Mn). But now this increase in F_{12} compared to IN_1 is by far more effective during the vegetation period (may through october).

Following the considerations given above it seems obvious that there does exist an input by aeorosols, IN_2, in the case of Na, Mg, Fe, Al, Cl and S, and very probably for K, Ca and Mn, too. For these elements $F_{12} > IN_1$, or $F_{12}/IN_1 > 1$ during the winter months, when we should expect the turnover being negligible.

On the other hand the same figures suggest that the turnover is of importance in the case of K, Ca and Mn : here the concentration increase within the flux F_{12} compared to the input IN_1 is extremely high during the summer months. This could also be due to a higher immission of these elements or to a higher filter action of the canopy during the vegetation period. The first does not hold true because the equivalent fraction in the open field precipitation is constant during the year (cf. fig. 2); the latter because the other elements are not affected in the same manner.

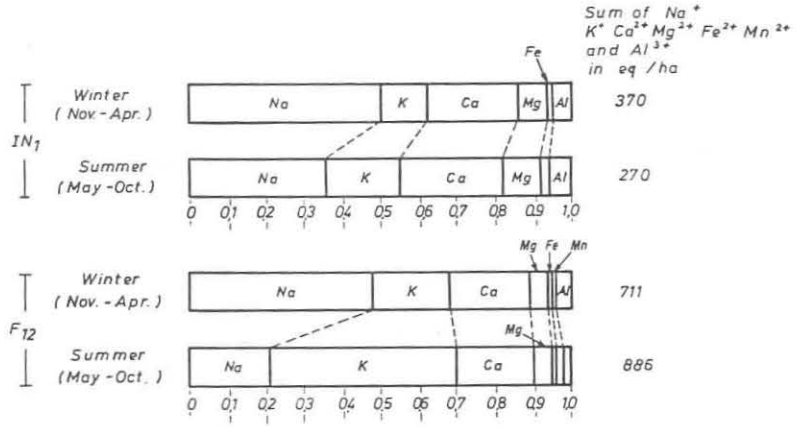


FIG. 2. — Equivalent fractions of cations in open field precipitation IN_1 and in stand precipitation F_{12} (average values June 1969 - May 1972)

Values for the input IN_2 (table 4) have been calculated separately for winter and summer according to the outlines given above :

$$\text{(W) winter : } IN_{2(w)} = F^{*}_{12(w)} - IN_{1(w)}$$

$$\text{(S) summer : } IN_{2(s)} = R.\ IN_{1(s)}$$

$$\text{where } R = \frac{IN_{2(w)}}{IN_{1(w)}} \qquad (5)$$

Annual values, $IN_2 = IN_{2(w)} + IN_{2(s)}$, are given in table 1 (7), values for the non-litter turnover, U, table 1(8), are calculated according to equation (3).

It is suggested by these figures that, for the most elements, the input by aeorosols is in the same order of magnitude (50 — 130 %) as the input by open field precipitation. Very little aerosol input seems to exist in the case of Al, moderate values are found for N, P and Mg, while the aeorosol input seems to be of main importance for Mn.

The figures calculated for the total element input ($IN_1 + IN_2$) can only be considered as rough estimates. The input-output analysis for the ecosystem may help to check these figures and eventually use them with more confidence.

INPUT - OUTPUT ANALYSIS

Basis for these considerations is the equation of continuity, valid for the ecosystem as well as for any of its compartments :

Input - Output = change in store

Using the symbols as introduced above, and Cn for the store (compartment size) of the n-th compartment, $\Delta\ Cn$ for the change of Cn with time, we may write the equation of continuity as

$$IN_1 + IN_2 - OUT = \sum_{n=1,4}{}' \Delta\ Cn \qquad (6)$$

Equation (6) can be simplified :

— it has been found that in the beech forest under consideration the leaf biomass (cycling fraction) does not change with time over the years, not taken into account seasonal variations. Thus, Δ C1 can be set to zero.

The same is true for Δ C2, if again we do not take into account seasonal variations.

Equation (6) then reduces to

$$IN_1 + IN_2 - OUT = \Delta C3 + \Delta C4 \quad (7)$$

Annual values for the wood increment (non-cycling fraction), Δ C4, are given in table 1.

A change in the element store of the solid phase (organic top soil and mineral soil), Δ C3, cannot easily be measured due to the spatial variability and due to the high total amounts of elements present in the soil. It is, though, possible to calculate Δ C3 from (7) by using IN_2 calculated above (table 1 (7)). We shall discuss the physical and biological meaning of the results for the elements individually. From our knowledge of the chemical properties of the soil we may, eventually, judge if our estimate of IN_2 is reasonalbe.

For calculation we rearrange (7).

$$\Delta C3 = IN_1 + IN_2 - OUT - \Delta C4 \quad (8)$$

The results are given in table 5; they are expressed in kg/ha, year and in % of F_{12} as the most important flux value used in the calculation of IN_2. The %-values may serve to judge wether the Δ C3 values are meaningful regarding the variability of the measurements.

TABLE 5

Calculated changes in compartment 3 *(soil solid phase)*

Δ C3	Na	K	Ca	Mg	Fe	Mn	Al	Cl	S	P	N
kg/ha, year	2.4	0.5	1.1	-0.8	1.0	-6.1	-5.3	-1.1	18.2	-1.9	8.2
in % of F_{12}	20%	2%	4%	21%	75%	200%	160%	3%	40%	380%	37%

Δ C3 reaches zero when the soil is in steady state in respect to an element. Positive values are met if the amount of element in soil is increasing, negative values when it is decreasing.

Since the variability of the flux measurements is in the magnitude of 30 % (MAYER, 1971) we may consider all values Δ C3 < 30 % of the flux F_{12} as being in steady state or close to it. This is the case for Na, K, Ca, Mg and Cl.

For chlorine the findings are in accordance with the missing absorption capacity of soils for the Cl^- ions.

For Na, K, Ca and Mg we know from chemical analysis of the soil (measurement of exchangeable cation stores at different times; calculation of the chemical potential for cation exchange reactions by downward transport of equilibrium soil solution; cf. ULRICH et *al.*, 1971) — that the soil is, in fact, in a steady state. The value for Na, though within the 30 % range, is higher than expected. This may be

due to an overestimation of the summer input by using the ratio R from equation (5) for calculation, because the Na input reaches extremely high values during hoar-frost periods. This is indicated in fig. 2, IN_1, in the higher Na equivalent frction in winter compared with summer. Thus the assumption of R being constant throughout the year is in this case incorrect.

The stores of Mn, Al and P in soil seem to decrease, provided the input with aeorosols is not underestimated. Though the latter cannot be excluded it is, on the other hand, very probable that considerable amounts of Al and Mn are exported from the soil with the percolation water as a result of the weathering of layer silicates (sorption of H^+ ions resulting in exchange of Al^{3+}, ULRICH et *al.*, 1971), and the dissolution of Mn (II) — compounds in the soil (this may be due to an acidification of the soil in recent decades by SO_2 immission). For phosphorus we may think of a liberation of P from Fe- and Al-phosphates.

In contrast to the elements mentioned above, the stores of Fe, S and N seem to increase, provided the input with aerosols IN_2 is not overestimated. This is quite unlikely since our estimates of IN_2 were rather on the minimum side. The effect may be readily explained for Fe; at the pH values prevailing in the subsoil the solubility of iron hydroxides is very low, Fe ions will therefore be precipitated and form iron oxides.

The increase of N may be due to the very high nitrogen input as a consequence of air pollution, which may date back only two or three decades, so that steady state in the organic top soil is not yet reached. The result is in agreement with the tendency for eutrophication visible in many forest ecosystems in Central Europe.

The increase of S, though relatively small compared to the total turnover rates, cannot be readily explained. It is known, that adsorption of sulfate is increasing rapidly with decreasing pH of soil (BARROW et *al.*, 1969). This, too, points towards an acidification of the soil in recent years.

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